

Pulsed Radio Emission from the Fermi-LAT Pulsar J1732-3131: Search and A Possible Detection at 34.5 MHz

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ABSTRACT

We report our search for and a possible detection of periodic radio pulses at 34.5 MHz from the Fermi-LAT pulsar J1732-3131. The candidate detection has been possible in only one of the many sessions of observations made with the low-frequency array at Gauribidanur, India, when the otherwise radio weak pulsar may have apparently brightened many folds. The candidate dispersion measure along the sight-line, based on the broad periodic profiles from ~ 20 minutes of data, is estimated to be 15.44 ± 0.32 pc/cc. We present the details of our periodic & single-pulse search, and discuss the results and their implications relevant to both, the pulsar and the intervening medium.

Key words: pulsars: general – pulsars: individual (J1732-3131)

1 INTRODUCTION

The Fermi Large Area Telescope (LAT) with its large effective area of ~ 9500 cm², large field of view (~ 2 sr), narrow point spread function $\sim 0.6^\circ$ at 1 GeV (normal incidence) and broad energy range (20 MeV - 300 GeV), is a highly sensitive instrument for γ -ray observations. Because of this vast improvement in sensitivity compared to past γ -ray missions, an extraordinary increase has been seen in the number of pulsars detected in gamma rays. Apart from the detection of gamma-rays from a large number of known pulsars, it was for the first time possible to perform blind searches for pulsars in γ -rays. These blind searches have so far discovered 33 γ -ray pulsars from the data recorded by the Fermi-LAT (Abdo et al. 2009; Saz Parkinson et al. 2010; Pletsch et al. 2012). There are mainly two kinds of competing theoretical models for the high energy emission from pulsars, viz. the Polar cap models and the Outer gap models. The ratio of radio-quiet to radio-loud γ -ray pulsars is an important discriminator between these two types of models. The LAT-pulsars discovered in blind searches need not necessarily be radio-quiet, and hence need to be searched for radio pulsations. Despite deep radio follow-up searches, so far only four of these LAT-discovered pulsars could be detected (J1741-2054, J2032+4127, J1907+0602 & J0106+4855; Camilo et al. 2009; Abdo et al. 2010; Pletsch et al. 2012), suggesting that the radio-quiet pulsar population might actually be quite

large. However, all the deep follow-up searches were carried out at high radio frequencies (around 1 GHz and above, except a few at 300 MHz; Ray et al. 2011; Pletsch et al. 2012), and the lower frequency domain still remains relatively unexplored.

At low radio frequencies the emission beams become wider (suggesting the so called radius-to-frequency mapping (RFM) of pulsar radio beams) increasing the probability of our line-of-sight passing through the emission beam. A classic example is B0943+10, which is detected only below ~ 1 GHz because our line-of-sight misses the relatively narrow emission beam at higher frequencies almost completely (see, for example, Weisberg et al. 1999; Deshpande & Rankin 2001). Also, recent study (Ravi et al. 2010) suggests that for high- \dot{E} (young) and millisecond pulsars, radio emission beam widths are comparable to those of γ -ray beams. Therefore such pulsars, if already detected in gamma-rays, can be expected to be beaming towards us. Given the widening of radio beams at low frequencies even for normal pulsars, follow-up searches of these γ -ray pulsars at very low frequencies (< 100 MHz) could also be revealing. Any detection would open an otherwise rare possibility of studying these objects at such low radio frequencies. On the other hand, a non-detection might provide stringent upper limits on the radio flux from these sources. Thus search for radio emission from LAT-discovered pulsars at low frequencies is essential for completeness before discriminating between the polar cap and outer gap models.

Many of the pulsars discovered by the Fermi-LAT lie in sky regions surveyed using Gauribidanur Telescope at 34.5 MHz in the years 2002 to 2006. We have searched the

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archival data of this survey, for periodically pulsed or any transient signal along the direction of 17 of these LAT-PSRs. Most of these remained undetected in both kind of searches. A second round of search and analysis using the same data but with relaxed thresholds is in progress. We present here detection of periodic radio pulses along the direction of the LAT-PSR J1732-3131 (Abdo et al. 2009), corresponding to period of 0.19652 ± 0.00003 seconds and dispersion measure of 15.44 ± 0.32 pc/cc. The results along the direction of other LAT-discovered pulsars will be reported elsewhere.

Section 2 describes the observations, and presents the result of the search carried out in the direction of pulsar J1732-3131. In section 3, we discuss the detection significance and present the estimates of flux density & distance to the pulsar, followed by conclusions in section 4.

2 SEARCH FOR SINGLE BRIGHT AND PERIODIC PULSES

2.1 Observations

Observations used here were made as a part of pulsar/transient survey, using the East-West arm of the radio telescope at Gauribidanur, India. The beam-widths (full width at half-power) of this arm are $21'$ and $25^\circ \text{sec}(\text{zenith} - \text{angle})$ in right ascension and declination respectively. The effective collecting area offered by this arm is about 12000 m^2 at the instrumental zenith ($+14^\circ.1$ declination). In each observing session, raw signal voltage sequence was directly recorded at the Nyquist rate (with 2-bit, 4-level quantization) using Portable Pulsar Receiver¹(PPR) for about 20 minutes, while tracking the source. For further details about the telescope we refer the reader to Deshpande, Shevgaonkar and Sastry (1989).

In the direction of the pulsar J1732-3131, data are available from 10 observing sessions of the above survey. The voltage time-sequence from each of these observing sessions was, in the off-line processing, Fourier transformed in blocks of 512 samples, resulting in dynamic spectrum with 256 spectral channels across 1.05 MHz bandwidth centred around 34.5 MHz, and temporal resolution of $\sim 1.95 \text{ ms}$ (after averaging 8 successive raw power-spectra). These resultant data in filter-bank format were subjected to two types of searches described in the following sub-sections.

2.2 Search for Single Bright Pulses

Periodic signals from pulsars at such low frequencies are generally very weak, and detectable only from a small fraction of the total pulsar population. However, it is not uncommon to find the strength of a single pulse, or a part of the pulse, increase many folds from its average (e.g. in the form of explicit excursion as in giant pulses/radiation spikes, or as a part of general sub-pulse level intensity fluctuations). How well such signals can be differentiated from mere noise fluctuations, or those due to radio frequency interference (RFI), depends not only on their relative strength, but also on their arrival times showing any specific correspondence

relative to the expected pulse arrival, and if manifestation of their propagation through the intervening medium, as for distant astronomical sources, is clearly evident.

The time of arrival of a pulsed signal varies across the frequency band because of the interstellar dispersion, a characteristic that serves as a primary identifier for signals from distant astronomical sources. The relative delay at a frequency ν with respect to a reference frequency ν_0 is given by: $\Delta t \text{ (ms)} = 4.15 \times 10^6 \times \text{DM} \times (\nu^{-2} - \nu_0^{-2})$; where ν and ν_0 are in MHz, and DM (Dispersion Measure in units of pc/cc) is the column density of electrons between the observer and the source, along the line of sight.

Search for single bright pulses looks for this dispersive signature across the observing band at each of the trial DMs, and reports its significance, in case of detection above a given threshold (see for example, Cordes & McLaughlin 2003). Further considerations are necessary to take in to account the effect of scattering in the intervening medium. Even for moderate DMs, the apparent pulse shape at such low frequencies is expected to be dominantly affected by the interstellar scattering. The resultant effect is usually modeled as a convolution of intrinsic pulse profile with a truncated (one-sided) exponential function. Thus, to enable optimum detection, a given dedispersed time-sequence was smoothed (match-filtered) with a truncated exponential template, before subjecting to detection criterion. This effectively provided a search also in the apparent pulse-width, when the templates of different widths were used in systematic trials. In our search for single pulses, with different trial DMs and smoothing widths, we found the highest number of pulses (10) exceeding our detection threshold of 4.5σ at a trial DM of 15.55 pc/cc, and a smoothing width of 8 samples, in contrast with the expectation of less than one pulse from noise excursions (specifically, 0.27 for the sequence of 77950 independent samples). These single pulses vary in their strengths from 4.5σ to 5.2σ , and were found to be distributed more or less uniformly throughout the total duration of the observation. When these 10 individual pulses (belonging to the DM-bin of width 0.29 pc/cc) were aligned and averaged together, the signal-to-noise ratio (S/N) improved as expected, providing a refined estimate of DM (15.55 ± 0.04 pc/cc). Figure 1 shows this average, where the dispersive nature of the resultant pulse in the dynamic spectrum is apparent. But, we need to remind ourselves that however appealing the appearance of such an average dispersed pulse may be, it is to be viewed with caution. A relevant illustration, though in a different context, can be found in Goldsmith et al. (2008), where constructive alignments and co-additions are shown to result in spurious peaks which are entirely due to random noise. The present situation is potentially no different from the above example, except that now we might have noise manifestations that are pre-selected on the criteria of better match with certain dispersive characteristics. When many such realizations are combined, as in our average of 10 pulses, naturally the result will show the same dispersive pattern even more clearly. The only parameter which will distinguish between possible spurious pattern and the real signal, if any, is the S/N of the resultant pattern. Hence, to assess the real significance of the resultant average pulse, the above procedure was repeated a number of times, in each using 10 strongest pulses at an arbitrarily chosen DM (understandably, this required us to reduce the threshold).

¹ http://www.rri.res.in/~dsp_ral/ppr/ppr_main.html (Deshpande, Ramkumar, Chandrasekaran & Vinutha, in preparation)

The corresponding average dedispersed pulse was found to be consistently weaker than that in figure 1. However, the difference was not very significant (S/N lower only by 1 or 2). This is not very surprising considering the fact that S/N of 4 out of the 10 pulses (at the candidate DM of 15.55 pc/cc) are only marginally above our detection threshold (a higher detection threshold of 5σ would have left with us only 2 excursions which are too few to seek a refined DM). Given this poor distinction between the average of ten pulses at the candidate DM and those at other DMs, the confidence with which inferences can be drawn about their possible association with the pulsar (assessed through their apparent longitudes), their average width and a refined DM they may imply, is rather limited, and these results are to be viewed with due caution².

2.3 Search for Periodic Pulsed Signal

Since the rotation ephemeris for the LAT-PSR J1732-3131 is known (Ray et al. 2011), folding the 20 minutes time sequence over the rotation period (after corrections for the barycentric motion of the Earth) was performed for each of the frequency channels to enhance S/N. Then, this “folded” dynamic spectrum was used to search for any significant dispersed pulse-profile. Peak S/N above a threshold was used as the criteria for detecting the candidates. However, highest S/N is expected when effective time resolution becomes equal to the pulse-width, so that all the flux in the pulse is integrated in just one sample. This becomes particularly important for a candidate having a large pulse-width (a number of reasons contribute to the apparent width; e.g., prominent effect of interstellar scattering at low frequencies, intrinsic pulse-width etc.). An optimum search across trial pulse-widths was thus carried out in each of the dedispersed-folded profiles. For completeness, we also extend the search

² Our detection threshold is admittedly and deliberately kept low (4.5σ) compared to commonly used thresholds, to minimize the probability of ‘miss’, which of course increases the false-alarm rate. Hence, there is a finite probability that some or most of these excursions may not correspond to the signal we are looking for. We note, however, that these observations were conducted at late night hours, when possible RFI is at its minimum, if not absent. The fact that the excursions span such a narrow range above our particularly low detection threshold, suggests to us absence of contamination from RFI, narrowing the causes to random noise or real signal. Quite independently, our pre-search processing looks for and excises any significant RFI that is narrow in bandwidth and/or in time. And, our procedure of normalizing the total power at each sample of the dynamic spectrum, removes all signals that are broadband *and* are of non-dispersive nature. Only those RFI which carry a dispersive signature, necessarily broadband, can escape this scrutiny. The “swept-frequency” RFI can indeed sometimes mimic the dispersive signature, normally identified with astronomical origin. However, the times of arrival of these “swept-frequency” RFI are generally linearly proportional to the frequency (as against the inverse-square dependence in case of astronomically originating signals). As part of further critical assessment, the data were dedispersed with linear delay gradients ($\Delta t \propto \nu$) spanning similar delay ranges, and the results were compared with those using ν^{-2} law. As would be expected for astronomical signal, the significance of detection is indeed lower for the linear chirp.

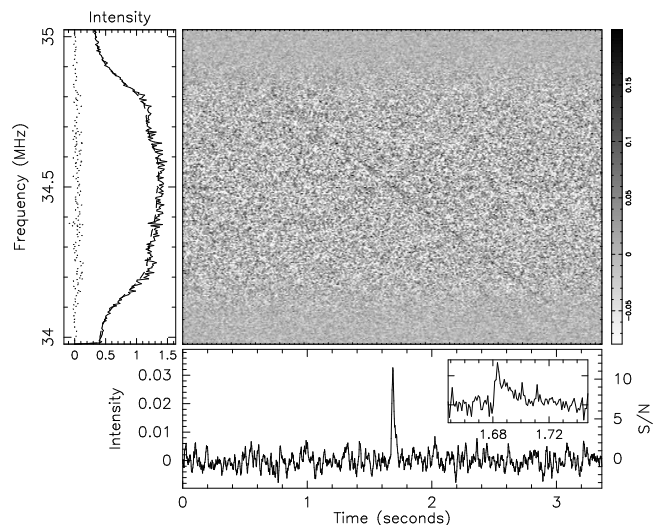


Figure 1. Dynamic spectrum of the 10 single pulses aligned and averaged together (to enhance S/N) is shown in the main panel. The data are smoothed by a rectangular window of width about 16 ms. The bottom sub-plot shows the pulse obtained after correcting for the delays corresponding to DM = 15.55 pc/cc. The left panel shows the average spectrum (dashed), the spectrum corresponding to the pulse-peak (solid) and the residuals (dotted) on the same scale. The inset in the bottom subplot shows average dedispersed pulse without any smoothing.

in the period domain (although over a narrow range of period offsets). In figure 2, we present a two-dimensional cut (DM and pulse-width) of the results of 3-D search procedure mentioned above, when applied to data from one of the observing sessions in 2002.

Clearly, a broad pulse is detected at DM of 15.2 ± 0.4 pc/cc; see the S/N profile in the bottom panel, where a broad S/N peak is seen in the range ~ 80 -180 degrees, indicating structures within the pulse on these scales. We note however that the S/N of the peak in the average profile as a figure of merit can lead to large errors in estimating the true DM when the individual frequency channel profiles have poor S/N, as is the case presently. There is also a related bias towards compactness of the average profile while searching for best-fit DM. We therefore use sum-of-squares (SSQ) of average intensities across the profile as a figure of merit. The significance of the average profile assessed in this manner and as a function of DM and period-offset is shown in figure 3. The isolated peak in figure of merit is striking and allows a less biased estimate of DM (15.44 ± 0.32 pc/cc), which we adopt in further discussion. Also, the period of 0.19652(3) seconds, suggested by this isolated peak, is consistent with that extrapolated from the available ephemeris (Ray et al. 2011), to the epoch of our observation (0.19652125(2) seconds).

In figure 4, the average profiles corresponding to the above mentioned two figures-of-merit are shown (peak S/N based : dashed-line; SSQ based : solid-line) for ready comparison. Both the profiles have been smoothed by only 25 degrees wide window, to retain the primary details in the profile, although the S/N would be less than optimum. We would like to emphasize here that although folding of ran-

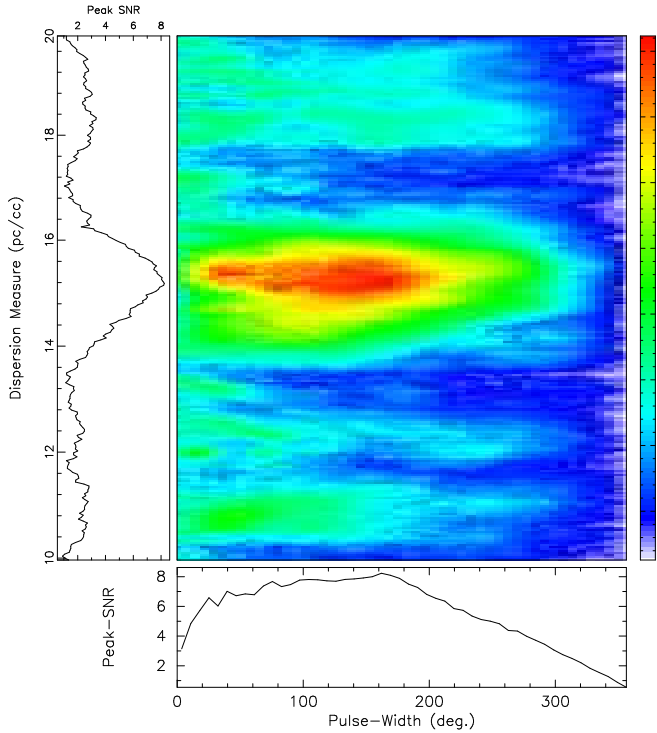


Figure 2. The body of the figure shows the peak-S/N in the folded profiles corresponding to each combination of the trial values of smoothing-width and DM. The plateau defining the preferred combinations is apparent in the range ~ 80 -180 degrees in smoothing-width, and ~ 14.8 -15.6 pc/cc in DM. For ease of viewing the typical variations, the left and bottom panels provide vertical and horizontal cuts at smoothing-width=160° and DM=15.19 pc/cc through the data plotted in the central panel.

dom noise can also produce impressive profiles (as exemplified in Ramachandran et al. 1998), peak amplitude in such profiles would still be constrained within the noise limits (i.e. full swing within 3 to 4 σ of the noise). In the present case, the peak-S/N in the average profile (figure 4; solid-line) is estimated to be 7. Here, the used value of noise standard deviation (in units of T_{sys}) is deduced directly from the time-bandwidth product, assuming only 75% of the total bandwidth. If we were to use a more optimistic estimate, using the rms-deviation computed from the dedispersed time sequence, the peak-S/N would exceed 9. It is clear that even the conservative estimate of the peak-S/N (7) is well outside the above mentioned threshold, and hence the claimed signal in the average profile can not be dismissed as mere manifestation of random noise.

2.4 Confirmatory Checks

To further assess the credibility of the above detection, the folded profiles prepared using the two halves of the frequency band separately, and those using alternate frequency channels were examined for the dispersion signature correspondingly. In another sanity check, a two-dimensional search in DM & pulse-width was carried out on the folded profiles made using only odd and even period-numbers separately. Both independently showed peak around DM ~ 15.4 pc/cc.

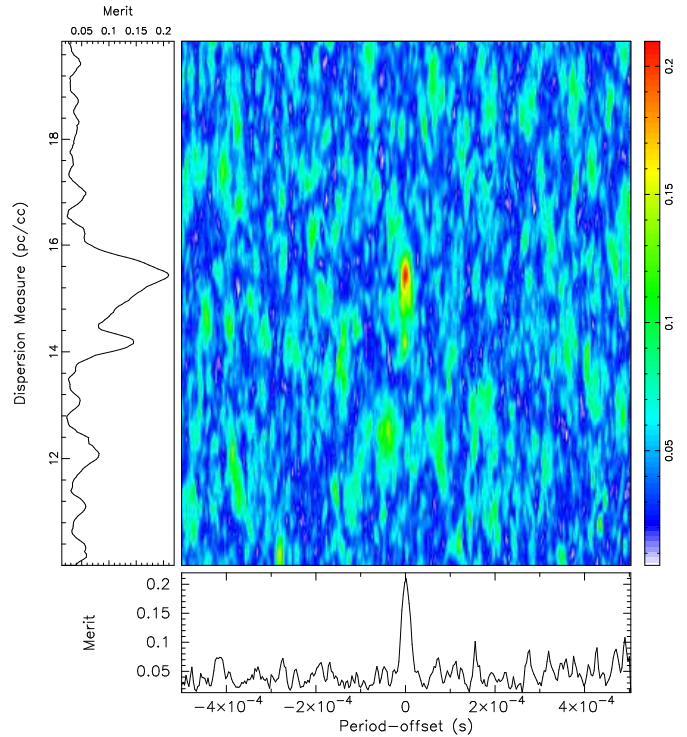


Figure 3. The main panel shows the significance of the folded profile as a function of DM and period. A narrow range of period-values around the actual period has been chosen. For the best-fit period, the figure-of-merit variations as a function of DM are shown in the left subplot. Corresponding to the best-fit DM (15.44 pc/cc), the bottom subplot shows the variations of figure-of-merit as a function of the period-offset.

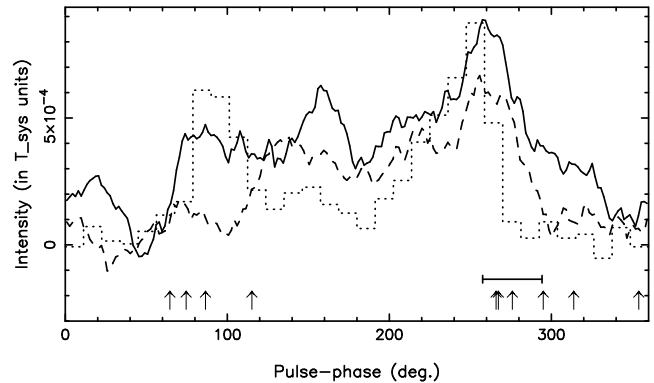


Figure 4. Average pulse-profiles at 34.5 MHz (solid & dashed; corresponding to DM = 15.44 pc/cc and 15.19 pc/cc respectively), a scaled version of the gamma-ray pulse-profile (dotted) and the positions of peaks of 10 bright pulses (arrow-marks) are shown together for ready comparison. The radio profiles were smoothed by a 25 degree wide window, and manually aligned with the gamma-ray profile. The horizontal bar denotes the average width of the bright pulses, which, on average, are about 200 times brighter than the peak intensity in the average profile.

We also carried out these searches on two fields observed on the same day just 20 minutes (in right ascension) prior to and after the field containing the candidate. No sign of dispersed signal around this period was found in either of the fields. This makes it unlikely that the above detection of a periodic signal could have been a result of some man-made or system originated signal.

Intriguingly, for rest of the 9 observing sessions, neither of the two kinds of searches showed any significant detection. We will discuss various possibilities which may have caused these non-detections, along with the implications of parameters determined from our data (table 1) in the following section.

3 RESULTS AND DISCUSSION

In figure 4, the average profile of the LAT PSR J1732-3131 at 34.5 MHz (solid-line) is compared with the pulse-profile as seen in gamma-rays (dotted-line) (Ray et al. 2011, see their figure 25). The radio profiles have been aligned with γ -ray profile manually, since the accuracy in the estimated DM value is not adequate enough for absolute phase-alignment. The apparent similarity between the profiles at these two extreme ends of the spectrum is striking, although there are possible differences. At radio frequencies, the significant pulsed emission is confined to about 70% of the period, with possibly bridging emission between the two gamma-ray components (i.e. between 120 to 220 degrees).

Origin of Single Pulses ?

The distribution of single bright pulses (figure 4; see the “arrow-marks”) in longitude is bimodal rather than uniform, visiting regions near the leading and trailing components of the main broad pulse in the radio-profile. Given that 1) no obvious association of these single pulses with any of the known pulsars is apparent (based on DM), 2) the dispersion measure suggested by these bright pulses ($DM=15.55 \pm 0.04$ pc/cc) falls within the error limits of that associated with the periodic signal (15.44 ± 0.32 pc/cc), 3) the profile shapes at these two DM values are indistinguishable (not shown in figure 4, but assessed separately), and 4) the position of these pulses are correlated with the outer regions of the pulse-window; it is difficult to rule out the possibility that these single pulses share their origin with the periodic signal. At the same time, the statistics of 10 pulses is too poor to rule out chance segregation in longitude. Giant pulses/radiation spikes are usually seen to confine themselves within the average pulse window (Lundgren et al. 1995; Ables et al. 1997). However, in the case of J0218+4232 (Knight et al. 2006), the giant pulses concentrate just outside the rising and trailing edges of the broad radio pulse, and those regions match the locations of the peaks in the high energy (x-ray) profile. If our single pulses are real, then their apparent distribution is reminiscent of the situation in J0218+4232, and the peaks in the gamma-ray profile could correspond to the single pulse locations if the gamma-ray profile was shifted by about 180° compared to what is shown in figure 4. Given this, and the apparent relative brightness of our single pulses, the possibility of their being giant pulses can not be ruled out.

Flux Density Estimate

The half-power beam-width at this declination is almost 35° (in declination). Therefore, we take the sky temperature estimates at various points across the beam from the higher resolution synthesis sky-map at 34.5 MHz (Dwarakanath & Uday Shankar 1990), and a weighted average of these using a theoretical beam-gain pattern provides us an estimate for the system temperature. For the present case, it is estimated to be 57000°K (receiver temperature contribution is negligible). Using this calibration, and assuming an effective collecting area of 8700 m^2 (in the direction of the pulsar) we estimate the average flux density (pulse-energy/period) of this pulsar at 34.5 MHz to be about 4 Jy.

Non-detection at Other Frequencies and in Other Observing Sessions

The mean flux density at 34.5 MHz, combined with the upper limit on the flux density at 1.4 GHz (0.2 mJy; Camilo et al. 2009), suggests a spectral index $\alpha \leq -2.7$ assuming no turn-over in the spectrum (a tighter upper limit given by Ray et al. 2011 from a deeper search suggests further steeper spectral index).

Although such a steep spectrum could explain the non-detection of the pulsar at higher frequencies, its detection in only one out of ten observing sessions at 34.5 MHz necessitates consideration of following possibilities :

1. **Extrinsic to the source:** This pulsar may actually be emitting below our detection limit, and favorable refractive scintillation conditions possibly raised the flux above our detection limit during one of our observing sessions.
2. **Intrinsic to the source:** The source may be an intermittent pulsar or a radio-faint pulsar which comes in “radio-bright” mode once in a while.

In either of the above possibilities, the spectral steepness mentioned above would be an overestimate.

Distance Estimates

For $DM=15.4$ pc/cc and location of the pulsar (RA=17:32:33.54, Dec=-31:31:23.00), the Cordes & Lazio (2002) electron density model (C&L model) yields³ a pulsar distance (d_{PSR}) of 600 ± 150 pc. This agrees well with the d_{PSR} estimates of $0.77^{+0.41}_{-0.35}$ kpc and $0.86^{+0.49}_{-0.30}$ kpc by Wei Wang (2011), using the correlation between the gamma-ray emission efficiency and a few pulsar parameters (generation-order parameter and B_{LC}). Alternatively, these distance estimates combined with the model electron density along the pulsar direction, give consistent DM value. However, the pulse broadening because of the interstellar scattering as predicted from C&L model (87^{+50}_{-35} ms), appears to be over-estimated by a large factor, given the narrow widths of bright pulses (about 20 ms or narrower) and the width of pulse components in the average pulse-profile.

³ The typical uncertainty in distance estimated using the C&L model, as quoted above, is believed to be 25%, however in some cases the estimates can be uncertain even by a factor of 2.

Table 1. Measured and Derived parameters for PSR J1732-3131

Known Parameters (from Ray et al. 2011)		Measured and Derived Parameters	
Right Ascension, R.A.(J2000.0)	17:32:33.54	Dispersion Measure, DM(pc/cc)	15.44 ± 0.32
Declination, Dec. (J2000.0)	-31:31:23.0	Best-fit Period, P_0 (s)	0.19652 ± 0.00003
Pulse Frequency, ν (s^{-1})	5.08794112	Epoch of period (MJD)	52384.9209
Frequency first derivative, $\dot{\nu}$ (s^{-2})	-7.2609×10^{-13}	Distance, d_{PSR} (pc)	600 ± 150
Epoch of frequency (MJD)	54933.00	Pulse Width, $\Delta\phi$ (degrees)	< 200

Follow-up observations at higher frequencies (100 to 300 MHz) and with better sensitivity would be useful in improving DM estimate, and for confirming the most likely association of the bright pulses with the pulsar. If confirmed, the comparison between the pulse profiles in the two extreme parts of the electromagnetic spectrum, and the location of bright single pulses would provide further insight into emission in the form of giant pulses (e.g. Hankins et al. 2003; Knight et al. 2006) or radiation spikes (e.g. Ables et al. 1997).

4 CONCLUSIONS

In this paper, we have presented results of our two kinds of searches (at 34.5 MHz) for radio pulses in the direction of the LAT pulsar J1732-3131, and report in detail an intriguing detection of periodic pulsed signal at DM of about 15.44 pc/cc. The possible reasons for its non-detection, in our other observing sessions and at higher frequencies, and related implications are discussed. The DM based distance estimate, using Cordes & Lazio electron density model, matches well with earlier estimates based on γ -ray emission efficiency. These results also demonstrate the potential and the importance of such searches/surveys at low radio frequencies. We hope our estimate of DM along with the other results will help follow-ups at suitable higher frequencies.

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